# Neutron Spin Filters Based on Polarized $^3$He

Spin-polarized neutrons are useful probes of magnetic matter since both the magnetic scattering of neutrons by unpaired electrons and the scattering of neutrons by nuclei of non-zero spin can be strong functions of the neutron spin state [1]. Unfortunately, the limitations of current polarizing and analyzing devices have substantially restricted the application of this powerful technique. $^3$He spin-filters have the potential to yield broadband neutron polarizers and analyzers that can be used for cold, thermal, and epithermal neutrons. Such spin filters could make new classes of neutron scattering experiments possible.

For certain applications there are presently no suitable devices. For example, polarization analysis of scattered beams having wide angular divergence is impractical with reflection-based devices such as supermirrors because of their inadequate angular acceptance and small-angle scattering. At present, we are developing $^3$He-based polarization analyzers for diffuse reflectometry and small-angle scattering (SANS) with neutrons, both of which require analysis of a large divergence beam. $^3$He-based neutron spin filters would also be advantageous on crystal spectrometers since any monochromator or analyzer crystal can be used, rather than just Heusler alloy, greatly increasing the range and flexibility of the instrumentation. Furthermore, polarizing or analyzing thermal and hot neutrons at spallation sources, where the time-of-flight method is employed, often requires the broadband capability of $^3$He spin filters. In addition to their utility for neutron scattering, polarized $^3$He spin filters are also of interest for nuclear and particle physics studies with neutrons, such as determination of weak coupling constants and tests of the Standard Model via accurate measurements of decay correlation coefficients in polarized neutron beta-decay [2].

Neutron spin filters based on polarized $^3$He rely on the strong spin-dependence of the neutron capture cross section for $^3$He. For a sufficient thickness of 100 % polarized $^3$He gas, essentially all of the neutrons with antiparallel spin would be absorbed, while nearly all of the neutrons with parallel spin would be transmitted, resulting in 100 % neutron polarization and 50 % transmission. In Fig. 1 we show calculated values of the neutron polarization $P_n$ and neutron transmission $T_n$ for $^3$He polarization $P_{He}$ = 60 %, an experimentally achievable value. Since there is a tradeoff between neutron polarization and transmission, we also show $P_n^2T_n$, which is a useful figure-of-merit for many experiments. A transmission analyzer can be characterized either by the transmission asymmetry $A$ or the flipping ratio $F$. For $T_+$ and $T_-$ defined to be the transmissions for neutrons with polarization parallel and antiparallel to the $^3$He polarization, respectively, the asymmetry is given by $A = (T_+ - T_-)/(T_+ + T_-)$ and the flipping ratio by $F = T_+/T_- = (1 + A)/(1 - A)$. The flipping ratio $F$ is also shown in Fig. 1. The asymmetry for a spin filter used as an analyzer is the same as the neutron polarization produced when it is used as a polarizer. For the specific case of cold neutrons ($\lambda$ = 0.5 nm), a spin filter used as a polarizer with $P_{He}$ = 60 % and a pressure-length product of 7 kPa·m would yield $P_n$ = 90 % and $T_n$ = 20 %, or, when used as an analyzer, would give $A$ = 90 % and $F$ = 19.

We produce polarized $^3$He gas by two optical pumping methods: spin-exchange, which is performed directly at high pressure (0.1 MPa to 0.3 MPa), and metastability-

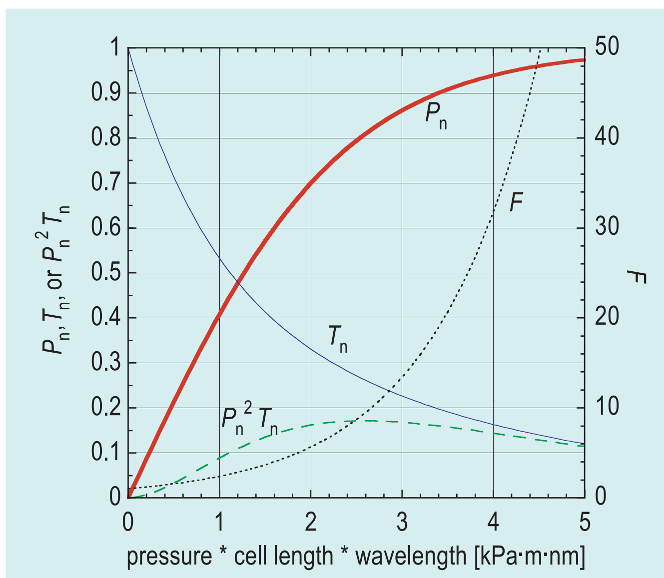


**Fig. 1. Neutron polarization $P_n$ (solid thick line), transmission $T_n$ (solid thin line), a figure of merit given by $P_n^2T_n$ (dashed line), and the flipping ratio $F$ (dotted line) as a function of the product of $^3$He pressure in Pa (assuming a room temperature cell), cell length in m and wavelength in nm. The calculations are shown for $^3$He polarization $P_{He}$= 60 %. The scale on the right hand y-axis is used for the flipping ratio.**

exchange, in which the gas is polarized at low pressure (≈ 100 Pa) and then compressed [3]. The spin-exchange method is convenient and well matched to continuous operation on a beamline, whereas the metastability-exchange method has a higher polarizing rate. At present, it has been more convenient (for either method) to polarize gas off-line and transport it to the beam line. Maintaining the polarization in the absence of optical pumping requires a homogeneous magnetic field and specially prepared glass cells with slow wall relaxation. We have produced cells with relaxation times as long as one month, dominated by the intrinsic dipole-dipole relaxation in the $^3$He gas itself [4]. In the future, continuously operating spin filters can be installed directly on the neutron instrument.

Polarization analysis allows for separation of magnetic from nuclear scattering, and also separation of coherent from spin-incoherent scattering. In our first demonstration experiment for SANS, we used a $^3$He spin filter to extract a small component of spin-incoherent scattering in the presence of strong coherent scattering [5]. We have continued with tests of separating magnetic from nuclear scattering.

Recently we carried out successful tests of a polarized $^3$He spin filter on the NCNR NG-1 reflectometer. The first test experiment on a specular reflection was a careful comparison of results obtained with a $^3$He analyzer to those obtained with the current technique that employs a supermirror analyzer. The test sample was an epitaxial $Mn_{0.52}Pd_{0.48}$/Fe (001) bilayer, for which chemical ordering and magnetic exchange-bias have recently been reported [6]. By varying the magnetic field on this sample, it was possible to test the $^3$He analyzer under conditions of both significant and negligible spin-flip scattering. We employed a compact, magnetically shielded solenoid that was interchanged with the analyzing supermirror on the NG1 instrument. The solenoid adequately shielded the stray fields from the 0.6 T magnet and guide field magnets. The results obtained with the $^3$He analyzer were identical to those obtained with the supermirror analyzer.

For efficient studies of diffuse scattering on a reflectometer, the $^3$He analyzer will be combined with a position sensitive detector (PSD). Two issues not tested in the specular experiment are relevant in this case: (1) possible depolarization of neutrons that follow trajectories off the axis of the $^3$He analyzer, and (2) possible background from the $^3$He cell. We have established that most of the area of apertures in the magnetic shield is usable, with depolarization only occurring for a small range of extreme trajectories. We have also determined that small angle scattering from the cell is negligible and therefore should not pose an issue for the low neutron fluxes expected in diffuse scattering experiments. This series of tests established the suitability of polarized $^3$He spin filters for diffuse reflectometry experiments, which we will pursue in the near future.

We are making continual improvements in the polarization and relaxation time of our $^3$He cells. In the recent reflectometry experiments, the initial $^3$He polarization was 57 %, resulting in a neutron flipping ratio of 31 and a transmission for the desired spin state of 24 %. The relaxation time of the polarized gas was 15 days on the beam line, which was somewhat reduced from the intrinsic value of 24 days for the cell due to a small fractional gradient of 3 x $10^{-4}$ $cm^{-1}$ in the magnetic field of the shielded solenoid. Our aim is to increase the $^3$He polarization to 70 % and obtain relaxation times at the dipole-dipole limit.

## References


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**T. R. Gentile and A. K. Thompson**
National Institute of Standards and Technology
NIST Center for Neutron Research
100 Bureau Drive, MS 8461
Gaithersburg, MD 20899-8461

**J. A. Borchers, J. W. Lynn, K. V. O'Donovan, and C. F. Majkrzak**
National Institute of Standards and Technology
NIST Center for Neutron Research
100 Bureau Drive, MS 8562
Gaithersburg, MD 20899-8562

**W. M. Snow and W. C. Chen**
Indiana University
Department of Physics
Bloomington, IN 47405

**G. L. Jones**
Physics Department
Hamilton College
198 College Hill Road
Clinton, New York 13323